Resilience metrics for transport networks: a review and practical examples for bridges

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Abstract

Climate change, diverse geohazards and structural deterioration pose major challenges in planning, maintenance and emergency response for transport infrastructure operators. Hence, to manage these risks and adapt to changing conditions, well-informed resilience assessment and decision-making tools are required. These tools are commonly associated with resilience metrics, which quantify the capacity of transport networks to withstand and absorb damage, recover after a disruption and adapt to future changes. Several resilience metrics have been proposed in the literature, however, there is lack of practical applications and worked examples. This paper attempts to fill this gap and provide engineers and novice researchers with a review of available metrics on the basis of the main properties of resilience, i.e. robustness, redundancy, resourcefulness and rapidity. The main steps of resilience assessment for transport infrastructure such as bridges are discussed and the use of fragility and restoration functions to assess the robustness and rapidity of recovery is demonstrated. Practical examples are provided using a bridge exposed to scour effects as a benchmark. Also, an illustrative example of a systems of assets is provided and different aspects of resilience-based decision making are discussed, aiming to provide a comprehensive, yet straightforward, understanding of resilience.

Keywords: bridges, transport management, climate change, resilience, restoration, fragility

1. Introduction

The concept of resilience has been widely adopted in infrastructure engineering and interconnected systems, e.g. transport, energy, health-care or communication networks (Argyroudis et al. 2020, Yodo and Wang 2016). These systems are subjected to external stressors such as man-made and natural hazards, some of them exacerbated by climate change effects (Mitoulis et al. 2021b). Resilience characterises the ability of a system to resist and absorb the impacts of disruptions due to external stressors (Bruneau et al. 2003), while encapsulates vulnerability, robustness, risk, reliability and adaptability (Faturechi and Miller-Hooks 2015). Bruneau et al. (2003) defined resilience of a physical or social system as a function of its **(1) Robustness** - the ability of the system or infrastructure to resist the impact of hazard events. This is typically expressed by the level of damage or functionality loss that the infrastructure suffers when subjected to a given hazard intensity. The damage and losses are commonly quantified through fragility, vulnerability and functionality loss functions (Pitilakis et al. 2016, Argyroudis et al. 2019) for abrupt hazards (e.g. earthquake), which in some cases consider asset's deterioration (e.g. corrosion) and cumulative effects such as sequencies of hazard events (e.g. Choe et al. 2009). **(2) Rapidity –** how quickly the system or infrastructure recovers after an event, which depends on the damage level and the available resources. This is usually estimated using restoration and reinstatement functions (Mitoulis et al. 2021a), which correlate time with the structural and traffic capacity gain, respectively. The downtime of the assets is critical for the estimation of indirect costs during the restoration of damaged or deteriorated components (Alipour and Shafei, 2016). **(3) Resourcefulness –** the ability to respond to an external threat either abrupt or evolving, by identifying the problems, providing resources and applying alleviation measures. **(4) Redundancy** – the extent to which the components of the systems can be replaced when the functionality has been partially or completely lost. Redundancy and resourcefulness are the means to improve the resilience of a system or infrastructure. For example, the resilience of a bridge can be enhanced by providing redundancy at material, member, and structural system level (Echevarria et al. 2016), while the resilience of a road network can be improved by ensuring that alternative routes can be used (Ganin et al. 2017), e.g. to cross a river in case of a flood event or during the restoration of deteriorated components.

Resilience is illustrated with Figure 1, which represents the robustness and rapidity of recovery. A hazard hits the infrastructure at time t_0, which causes a drop in the quality or performance of the infrastructure Q, e.g. loss of functionality. The extent of loss depends on the vulnerability of the infrastructure *(A-B)*, and is lower if the robustness *(B-C)* is high. The recovery is completed at time t_1, i.e. the duration of the recovery is equal to t_1-t_0, and its rapidity depends on the level of damage, as well as the available resources, redundancies and policies or decisions taken by infrastructure operators. The recovery is commonly initiating at time t_R, after an idle period (t_R-t_0), when no works are taking place, and this includes the inspection and assessment of the asset (e.g. by competent personnel such as divers for underwater inspection in case of river-crossing bridges), the design of the restoration works or other delays due to sequence of hazards, e.g. prolonged rainfalls. The variability in the idle time depends on the available resources, the extent of damage and local practices (Mitoulis et al. 2021a). A simplified version of the resilience curve is the resilience triangle (ABD), which represents a linear recovery of Q over time (Bruneau 2003, Zobel 2011).

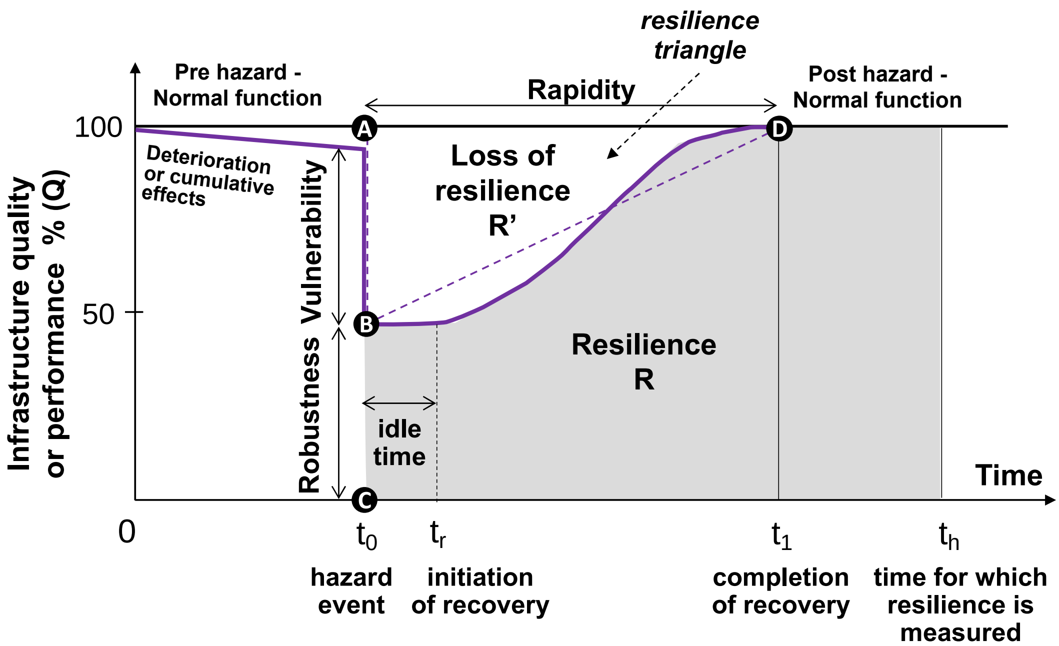


Figure 1. Infrastructure resilience expressed as performance over time

A resilience curve is a graph commonly used in the critical infrastructure domain, to illustrate system's resilience, i.e. evolution of system performance over time for given scenarios of disruption. Resilience metrics have been introduced to quantify resilience based on the shape and dimensions of the resilience curve, e.g. the duration of the restoration or the residual functionality of the infrastructure, and they are defined as summary metrics (Poulin and Kane, 2021, Ayyub 2014). These metrics are used to rank the assets of an infrastructure, e.g. a portfolio of bridges in a highway network, on the basis of their resilience for given hazard scenarios. Also, they are used to reflect the impact of different restoration or adaptation strategies for different hazard events, and hence they can support decision making. Poulin and Kane (2021) presented a taxonomy of resilience curve and summary metrics. They classified metrics in the following categories: magnitude (e.g. restored or residual performance), duration (e.g. disruption), integral (cumulative impact or performance), rate (e.g. failure or recovery), threshold and ensemble (e.g. weighted indexes). Argyroudis et al. (2020) introduced a framework for the resilience assessment of infrastructure assets exposed to multiple hazard events, e.g. sequence of flood events or flood followed by earthquake, considering if the damaged asset is fully, partially or not restored between subsequent hazard occurrences.

On a network level, Sun et al. (2020) conducted a comprehensive review of different resilience metrics for transport infrastructure, including functionality and socioeconomic resilience metrics. Examples of functionality metrics is the connectivity or centrality of transport networks, and other traffic related metrics such as travel time, throughput, or congestion index. Socioeconomic metrics are distinguished in system-based (e.g. business continuity and operability after extreme events) and capital-based. Twumasi-Boakye and Sobanjo (2018) presented a framework for regional road network resilience assessment using traffic modelling and GIS techniques for different hazard scenarios. The network resilience was quantified based on performance indicators such as the vehicle distance and hours travelled for the areas affected by bridge closures. Similarly, the total travel time and total travel distance were adopted by Bocchini and Frangopol (2012) as resilience measures of the network by considering multiple bridge configurations based on their proposed resilience assessment concept. Panteli et al. (2017) suggested time-dependent resilience metrics for power systems to capture the degradation and recovery features for different phases of an event, i.e. disturbance progress, post-disturbance degraded, and restorative. The same research distinguishes between ‘operational’ resilience, i.e. ability to ensure the uninterrupted supply to customers, and ‘infrastructure’ resilience, i.e. physical strength of a system for mitigating damage.

Lounis and McAllister (2016) introduced a framework for risk-informed decision making of infrastructure facilities inclusive of sustainability and resilience concepts. The sustainability considers environmental impacts, while resilience assessment is based on the damage level and loss of functionality following a hazard event, the recovery times of the functionality and the associated costs. With respect to the variation in the demand for service at community level following a disaster, Didier et al. (2018) proposed resilience measures considering demand, supply and consumption at component and system level. The metric of redundancy and robustness is described by the supply reserve margin (i.e. the difference between supply capacity and demand), while the resourcefulness and the rapidity of the recovery is measured by the notion of resilience time (i.e. time during which a supply deficit). To evaluate the resilience of interconnected systems, Reed et al. (2009) proposed a function that combines the discrete resilience metrics, considering the level of systems inter-connectivity.

An important aspect is the uncertain factors that may affect the resilience assessments. De Iuliis et al. (2021) applied Bayesian network models to address uncertain parameters and interdependencies involved in the assessment of infrastructure recovery process, including financing planning, availability of human resources, and regulatory and economic uncertainties. Similarly, Hosseini and Barker (2016) and Hosseini and Ivanov (2019) proposed a measure that quantifies system resilience as a function of vulnerability and recoverability using Bayesian network and considering disruption propagation aiming to support decision-making in functionality restoration and planning preventive safety measures.

The present paper provides an overview of the most common resilience metrics (section 2), including the parameters and input that are needed in each metric. The main steps for the quantification of resilience are described (section 2.1), including the use of fragility and restoration functions with illustrative examples for a benchmark bridge exposed to a range of realistic scour scenarios (sections 2.2-2.3). Subsequently, resilience curves and metrics are calculated for the same benchmark bridge (section 3) and the results are discussed, aiming to provide a simple but descriptive demonstration understanding of the use of resilience metrics and their value in decision-making and asset management. An illustrative example of a highway network is also shown (section 4) and the practicality of resilience metrics for the decision-making and prioritisation of assets by stakeholders is discussed.

2. Overview of resilience metrics

Resilient metrics aim to quantify the strength, functionality, and recovery-time of an infrastructure asset or network, following a disruption, as a result of either abrupt events, e.g. flash floods or earthquakes, or gradually developed effects, e.g. corrosion of structure material or slow ground movement; yet, the latter is also covered by maintenance methods and life cycle analysis, therefore resilience mainly quantifies performance for unforeseen high-impact threats. Table 1 summarises representative resilience metrics, including their mathematical formulation and the definition of the metric parameters, along with explanations and comments. The list is not exhaustive and intends to provide the practical and commonly used measures of resilience, with focus on transport infrastructure, such as bridges. Most of the metrics are related to the concept of resilience curve shown in Figure 1. Robustness represents the remaining functionality of the infrastructure just after the disturbance occurrence, while the rapidity describes the slope of the resilience curve (Ayyub, 2014). One of the first metrics introduced in the literature is the area within the resilience curve or resilience triangle (Bruneau et al. 2003), which describes the loss of resilience (*R'*), meaning that larger areas correspond to greater loss and lower resilience. The most common measure of resilience is the area under the resilience curve (*R*), suggested by Bruneau and Reinhorn

(2007); in this case larger areas correspond to higher resilience. Resilience can be normalised with respect to the recovery time *(t_1-t_0)* or with the maximum recovery time of a portfolio of assets (Cimellaro et al. 2009, Attoh-Okine et al. 2007) or other control time, e.g. one year, as suggested by Minaie and Moon (2017). This normalisation allows the comparison of the resilience of different assets, for prioritisation purposes.

However, when the resilience of an asset, e.g. a bridge or a network, is quantified based on the area inside or outside the resilience triangle or curve, then it is possible that different scenarios correspond to the same resilience values. For example, a bridge with relatively small loss of functionality, can be repaired in a longer period due to lack of resources compared with another bridge with greater loss of functionality and/or higher importance. The resilience values (area within the resilience triangle) can be very similar, although these two cases correspond to completely different scenarios. In this respect, Zobel (2011) introduced the 'adjusted resilience' function to represent different perspectives of the decision maker based on an optimisation model, which accounts for the upper bounds of manageable levels of recovery time and infrastructure loss as per the infrastructure owner perception. This approach is visualised through a series of hyperbolic curves corresponding to different combinations of robustness and rapidity for a given resilience value.

Argyroudis et al. (2021) introduced a cost-based resilience metric for bridges, considering the direct cost (physical damage), indirect cost due to detour of the traffic and the socioeconomic impact of the traffic disruption. This metric provides a more comprehensive assessment of the resilience since the indirect and socioeconomic impact can be far greater that direct loss. Minaie and Moon (2017) introduced a qualitative assessment of the robustness of bridges for multiple hazards, using four factors, i.e. hazard, importance, vulnerability and uncertainty. They also estimate an adjusted recovery time accounting for local practices, history of events and bridge types. This indicator-based approach, although admittedly simplistic, facilitates practical and rapid assessments for a portfolio of bridges exposed to various hazard effects.

Ayyub (2014) suggested resilience metrics accounting for ageing effects of the asset, using a Poisson model to define the occurrence of the hazard incident. In this respect, the failure can follow different paths, i.e. brittle, ductile or graceful. Finally, Sharma et al. (2018) proposed a set of mathematical formulations that describe the resilience curve of engineering systems, i.e. centre of resilience, resilience quantile, median and mode of resilience, resilience skewness, and resilience moment. A stochastic approach for the modelling of the recovery is adopted, which can incorporate empirical or expert elicitation data, while damage states are defined using reliability and safety concepts. This approach is suitable for life-cycle analysis and resilience-based design of infrastructure systems.

Table 1. Summary of representative resilience metrics sorted in order of complexity

reference	mathematical formulation	parameters of the resilience metric	comments and/or advantages & disadvantages
Ayyub (2014)	Robustness = B – C Rapidity = $\frac{A-B}{t_1-t_0}$	See Figure 1	Robustness units: percentage Rapidity units: average recovery rate in percentage per time Simple and straightforward metrics, easy for comparisons
Bruneau et al. (2003)	Loss of resilience R' $R'=\int_{t0}^{t1}[100-Q(t)]dt$	Q(t): the infrastructure quality, or performance of a system at a given time t. t_0 : the time of incident or disturbance occurrence. t_1: time when restoration is completed (quality of infrastructure is 100%). See symbols in Figure 1	R' corresponds to the area above the resilience curve measured from t_0 to t_1 Different scenarios may correspond to the same R values
Bruneau and Reinhorn (2007)	Resilience R $R=\int_{t0}^{t1}Q(t)dt$	Same as above	R corresponds to the area below the resilience curve measured from t_0 to t_1 Different scenarios may correspond to the same R values
Attoh-Okine et al. (2007)	$R=\frac{\int_{t0}^{t1}Q(t)dt}{100(t_1-t_0)}$	Same as above	Units: performance per unit time, where performance can be measured in percent (Figure 1).
Cimellaro et al. (2009)	$R=\frac{\int_{t0}^{th}Q(t)dt}{(t_h-t_0)}$	t_h: time horizon (for a portfolio of bridges this can be the maximum recovery time).	R is calculated for a larger period t_h (or time horizon), so that a faster recovery results to higher values of R.
Minaie and Moon (2017)	Resilience R, for a control time of one year $R=\frac{\int_{t0}^{t0+365days}Q(t)dt}{\int_{t0}^{t0+365days}Q(100\%)dt}$ $=2.74\times10^{-5}\times\int_{t0}^{t0+365days}Q(t)dt$	Q(100%): performance at 100% level. t_0 : time that extreme event hits. $2.74\text{x}10^{-5}$: constant calculated based on the area under the 100% performance level over the control time of one year.	The following resilience ranking scale is proposed: R= 91-100: very high; 81-90: high; 61-80: moderate; 41-60: low; 21-40: extremely low; 0-20: non-resilient

Zobel (2011)	For the resilience triangle (Figure 1), the equation of R simplifies to: $R = \frac{T^* - \frac{XT}{2}}{T^*} = 1 - \frac{XT}{2T^*}$	$T = t_1 - t_0$: time to recovery. $T^* = t_h - t_0$: time extending after recovery for which R is measured. $X = 1 - Q(t_0)$: initial loss of functionality.	The minimum value for R is 0.5, and the maximum is 1.0.
Argyroudis et al. (2021)	Cost-based resilience R_C (for bridges) $R_C = R \cdot \left(1 - \frac{C_D}{C_D + \gamma C_{IN}} \frac{C_{IN}}{C_{IN,max}}\right)$	C_D : direct cost C_{IN} : indirect cost (e.g. due to traffic diversion) γ : factor that takes into account the socio-economic impact of the indirect cost on the network operation considering e.g. damage extent, daily traffic, or accessibility to critical facilities. A rational range of γ is between 0.05 and 0.15. $C_{IN,max}$: maximum indirect cost for a portfolio of bridges	R here is the typical resilience metric (as per equations above) R_C is more comprehensive, as it also includes cost assessments; however, the estimation of indirect cost needs further data and analysis
Ayyub (2014)	Resilience R_e: $R_e = \frac{T_i + F\Delta T_f + R\Delta T_r}{T_i + \Delta T_f + \Delta T_r}$ Failure profile : $F = \frac{\int_{t_i}^{t_f} f dt}{\int_{t_i}^{t_f} Q dt}$ Recovery profile: $R = \frac{\int_{t_f}^{t_r} r dt}{\int_{t_f}^{t_r} Q dt}$	T_i : time to incident. T_f : time to failure. T_r : time to recovery. ΔT_f : failure duration. ΔT_r : recovery duration. ΔT_d : duration of disruption ($\Delta T_f + \Delta T_r$). t_f : end of failure event. tr : end of recovery.	Different failure (brittle, ductile, graceful) and recovery scenarios are considered, including either expeditious recovery to: better than new, as good as new, better than old, or as good as new, or standard recovery to as good as old, or worse than old. R_e includes realistic failure and recovery scenarios, both abrupt and evolving conditions are considered.
Minaie and Moon (2017)	Robustness P_R (for bridges): P_R = [100%-max(9.259xHxVxUF)xI] P_R: 0-100%	I: importance factor. I= 0.75, 1.00 or 1.25, depending on the importance of the route, utility lines carried, replacement cost, average daily traffic, and detour length. H: hazard factor. H= 1, 2 or 3, depending on hurricane or liquefaction risk, distance from the coast, potential for scour, history of hazard (*for geo/hydraulic hazards*) and seismic design level, history of previous events, distance from heavy industry, daily traffic (*for seismic, collision, fire, fatigue, overload*). V: vulnerability factor. V=1, 2 or 3, depending on the type of foundation, protection standards, design codes, type of bearings, history of damage etc. UF: uncertainty factor (depending on the evaluation practice). UF= 1.0 (visual inspection), 1.10 (visual and analytical techniques), 1.20 (visual, analytical and non-destructive evaluation).	HxV is calculated separately for each hazard and vulnerability category. P_R is calculated representing the worst-case scenario as an envelope of all hazard and vulnerability combinations that could possibly cause interruption of performance. This is a simplistic, yet, qualitative approach, which is easy to apply for rapid assessment of large portfolios of assets *For more details, see Minaie and Moon (2017)*
	Recovery time t_{rec} : $t_{rec} = t_{res} \times \alpha_1 \times \alpha_2 \times \alpha_b$	t_{res} : basic restoration time, depending on the severity of hazard and area affected, e.g. ranging from 1 day for low hazard and localised impact to 24 months for catastrophic hazard with regional impact. $\alpha_1, \alpha_2, \alpha_b$: adjustment factors.	α_1 = 0.8 or 1.0, based on agency's extreme event management practices, α_2 = 1.0, 1.2, 1.4, or 1.6 based on history of extreme events in the past year, α_b : 1.0, 1.15, 1.3, 1.5 based on bridge type and length.

2.1 Resilience assessment

In order to assess the resilience of an asset, e.g. a bridge, it is important to define: (I) the typology of the asset, (II) the hazard scenario and the corresponding intensity measure, e.g. scour or flow depth for river flooding or PGA for earthquakes, (III) the expected damage and losses for the given intensity, (IV) the measure of asset's performance and its recovery with time, as well as (IV) the resilience metrics and time horizon for which the assessment is performed (Figure 2).

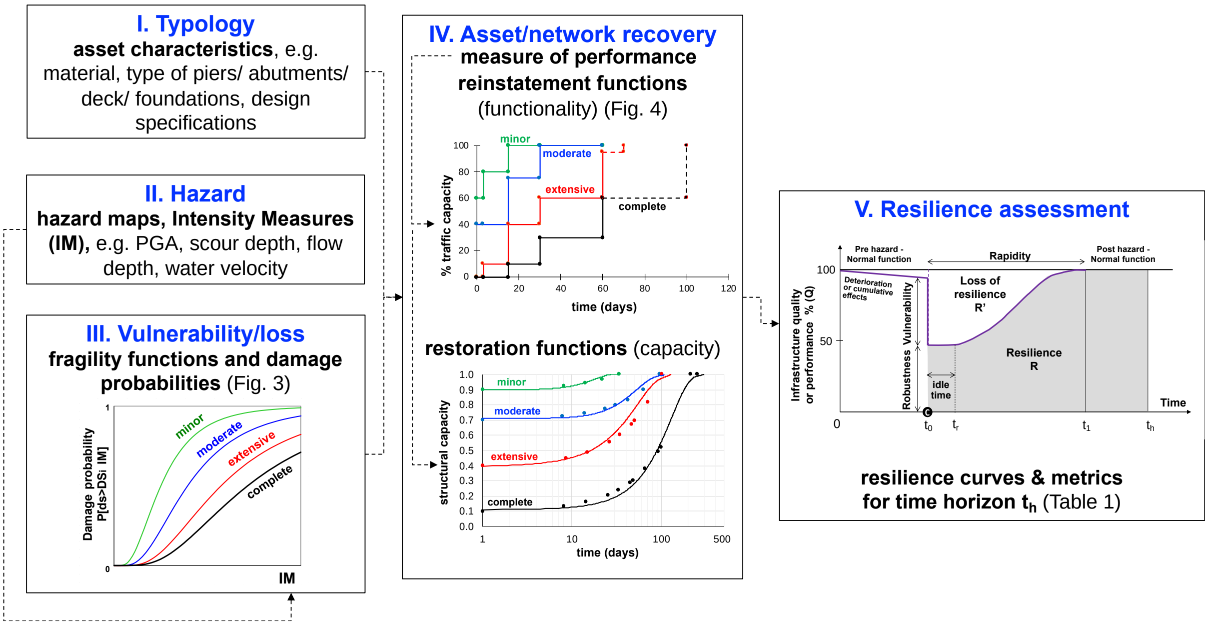


Figure 2. Main steps for resilience assessment of infrastructure assets

The **typology** of the asset includes the characteristics of the structure, such as material, foundation type, structural type, type of piers, abutments, deck and design specifications. These properties are required to understand the failure mechanisms of the structure and to assess the expected level of damage, the loss of functionality and the rapidity of recovery, based on fragility and restoration functions (see section 2.2). For more details on the typology of bridges refer to Argyroudis and Mitoulis (2021), Pregnolato (2019) for flood effects and Tsionis and Fardis (2014) for seismic hazard. **Hazard** includes either abrupt events, e.g. floods, earthquakes, landslides or evolving conditions of deterioration, corrosion or accumulation of damage, which cause a rapid or gradual drop of asset's performance. The hazard is measured with different **intensity measures** such as water discharge, velocity or depth for flood, and PGA for earthquake. For the resilience assessment, different hazard scenarios are usually be selected, corresponding to different return periods and intensity levels. Hazard maps and data can be found in Woessner et al. (2015) for earthquakes and Alfieri et al. (2014) for floods in Europe. The intensity measures are required for the quantification of losses using **fragility functions**, while the efficiency, sufficiency and practicality of different intensity measures depends on the typology of the asset, the hazard and the analysis approach, e.g. see Padgett et al. (2008), Huang et al. (2021). The **measure of performance** is a measure of the availability, productivity, and quality the of infrastructure (Poulin and Kane, 2021), and is usually measured on a scale of 0 (not functional) to 100% (fully functional). For a bridge, this describes its traffic capacity, i.e. how much of the traffic can be accommodated if the bridge suffers a given degree of damage or degradation, or its structural capacity, i.e. depending on the capacity of the bridge components and the definition of damage states in the fragility functions. This is important to define the indirect losses, i.e. those related to delays or detour of the traffic, as well as to describe the gradual restoration of the lost functionality with time through **restoration functions** (see section 2.2). The resilience assessments are performed using representative **metrics** (Table 1) and they are usually normalised to a **time horizon** to facilitate comparisons for different assets, hazard scenarios and hence different losses and recovery times. For example, Ouyang et al. (2012) and Minaie and Moon (2017), suggested a control time of one year for bridges, to compare a portfolio of bridges based on their annual resilience. In other applications, the maximum recovery time is used (Argyroudis et al. 2021) or a given time-interval associated to design hazard return period or infrastructure lifecycle (Li et al. 2020, Dong and Frangopol, 2016). In some cases, the resilience assessments are normalised to a reference target performance set by stakeholders (Poulin and Kane, 2021).

2.2 Fragility and restoration functions

The loss of asset performance can be defined using fragility, vulnerability or functionality loss functions. These functions can be derived based on empirical data, numerical simulations and/or elicitation approaches (Argyroudis et al. 2019) and they provide a quantification of the asset's robustness. **Fragility functions** correlate the hazard intensity measure with the probability of exceeding a certain damage level (e.g. minor, moderate, extensive, complete) and they are usually defined as two-parameters lognormal distribution functions, e.g. see Argyroudis and Mitoulis (2021) for bridges subjected to flood, Stefanidou and Kappos (2021) for earthquakes, Balomenos et al. (2020) for hurricane loads, and Gidaris et al. (2017) for multiple hazards. Figure 3 illustrates how for a given hazard intensity (step 1), in this case a scour depth equal to 2.0m, the probabilities of damage exceedance and occurrence obtained from the fragility curves (steps 2 and 3) are used to estimate the direct (physical) loss (steps 4 to 6) for a three-span reinforced concrete integral bridge with shallow foundations. The expected loss is calculated based on an average cost ratio (CR in step 4), i.e. the ratio of damage repair to replacement cost (see Mitoulis et al. 2021a, for flood damaged bridges, McKenna et al. 2021, for highway embankments and Mackie et al. 2007 for post-earthquake bridge damage).

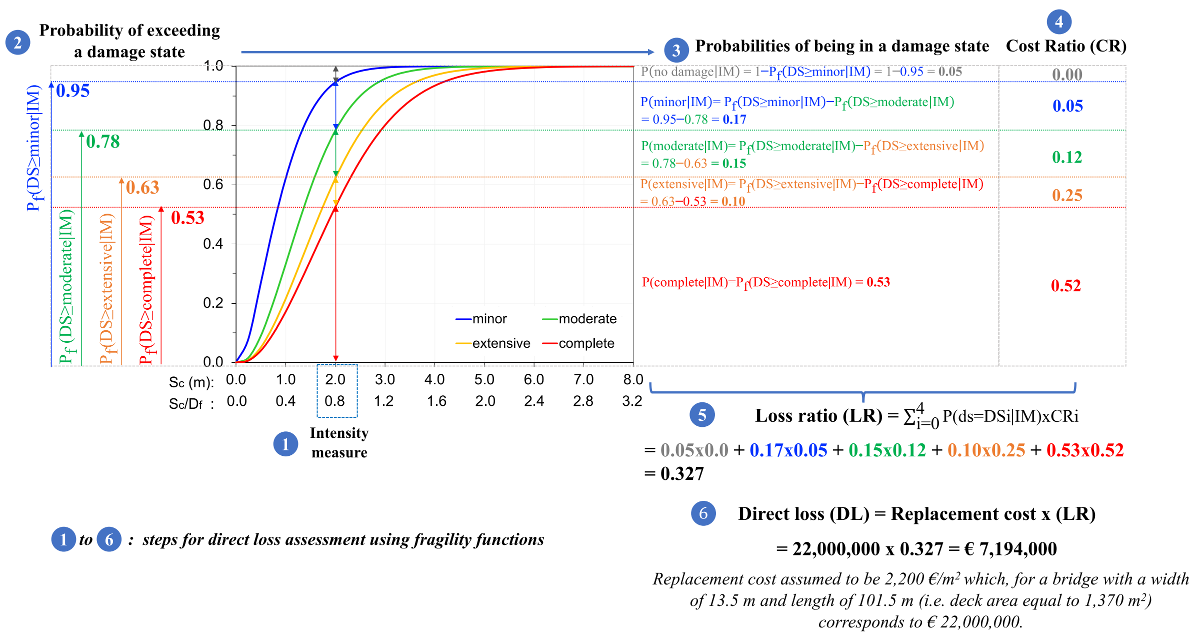


Figure 3. Example of direct loss assessment (steps 1 to 6) for an integral reinforced concrete bridge with shallow foundations subjected to scour depth of S_c=2.0m (the ratio of the scour depth to foundation depth is 0.8). The fragility functions are provided in Argyroudis and Mitoulis (2021) for minor, moderate, extensive and complete damage, and the cost ratios are obtained from Mitoulis et al. (2021a).

Restoration functions correlate the recovery time with the infrastructure performance or functionality level for different damage levels of the asset under study. They are based on expert opinion and/or empirical data and can be linear or S-shaped (Sharma et al. 2018). The recovery time depends on different factors, such as the available resources, the extent of damage, or the priorities and practices of the infrastructure owner, and hence, it contains many uncertainties. The available restoration models are rather limited. Mitoulis et al. (2021a) proposed models for the restoration of structural capacity and the reinstatement of traffic for bridges damaged by flood and scour effects using questionnaires to experts. The models considered the sequence and dependencies of restoration tasks, repair costs and durations and idle times. Also, Misra et al. (2020) conducted an expert-opinion survey to elicit the time required to remove traffic closures for roadway and bridges after earthquakes, hurricanes, flood-induced scour and tsunami/hurricane surge. Figure 4 shows how the damage probabilities obtained from the fragility functions, are used to calculate the post-flood gain of the bridge capacity (Figure 4a) and traffic capacity (Figure 4b) at a given time after the initiation of restoration works using restoration and reinstatement functions. In this example, the expected capacity of the bridge after 10 days is 42.3% and the traffic capacity is 25.6%. It is noted that the traffic capacity on day 1 is the remaining capacity of the bridge before the initiation of any restoration works.

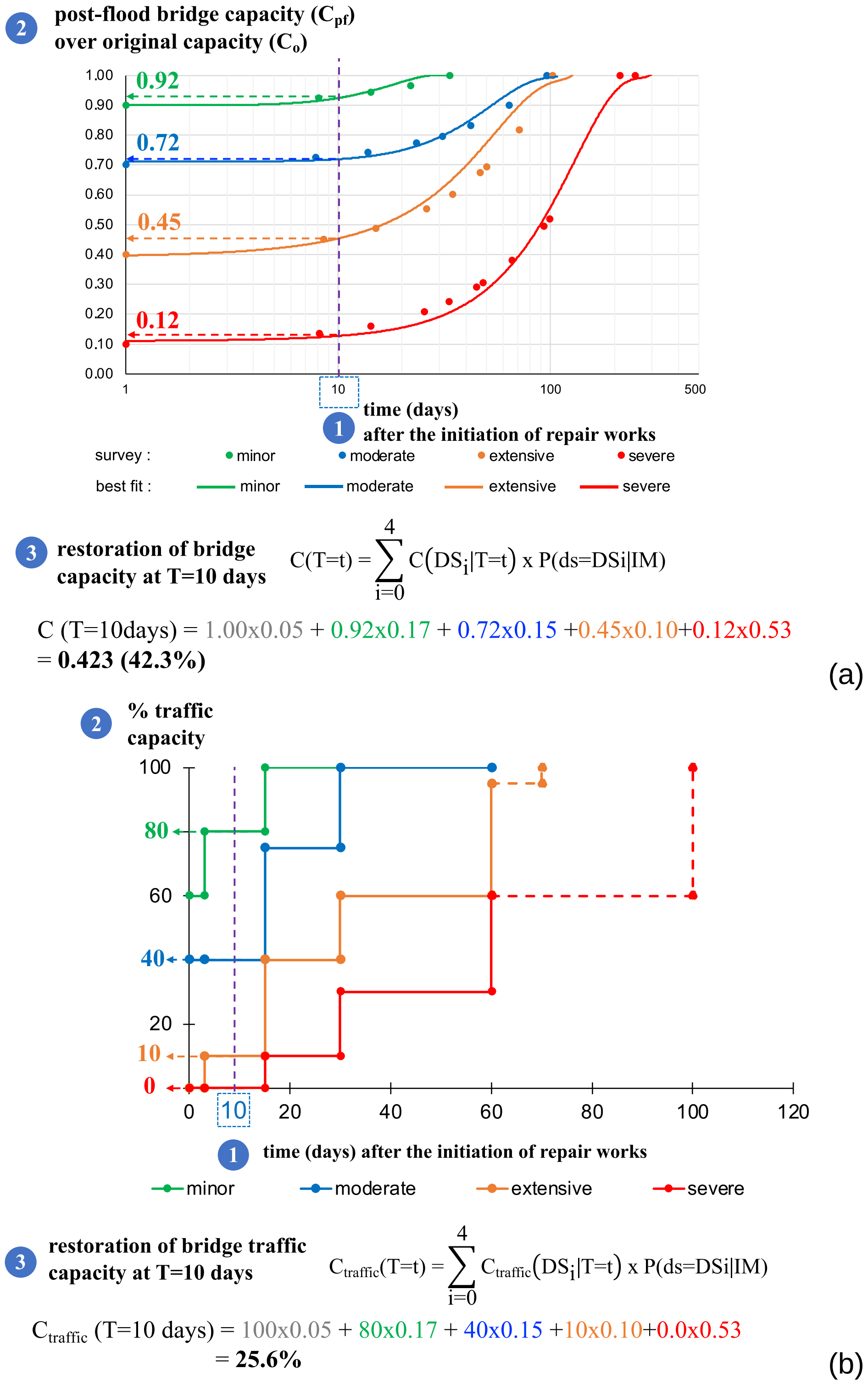


Figure 4. Example of (a) structural capacity and (b) traffic capacity assessment for a bridge with shallow foundations subjected to scour depth of S_c=2.0m. The damage probabilities P(ds=DSi|IM) are taken from Figure 3. The restoration (a) and reinstatement (b) functions proposed by Mitoulis et al. (2021a) are used (dashed lines correspond to projections based on engineering judgement) and the capacity restored at 10 days after the initiation of the restoration works is assessed.

The assessment described above follows a probabilistic approach, where the occurrence probabilities of different damage levels are used to calculate a weighted average loss (Figure 3) and capacity level (Figure 4) for a given hazard intensity. The fragility curves in these examples describe the performance of the entire bridge (system fragility), similar estimations can be made at component level (e.g. deck, piers, abutments) using the corresponding component fragility functions (see Argyroudis and Mitoulis 2021 for flood effects, or Stefanidou and Kappos 2017 for seismic effects). In this case, adjustments on the restoration times should be made, considering the component damages and restoration tasks (see Mitoulis et al. 2021a, Karamlou and Bocchini 2017).

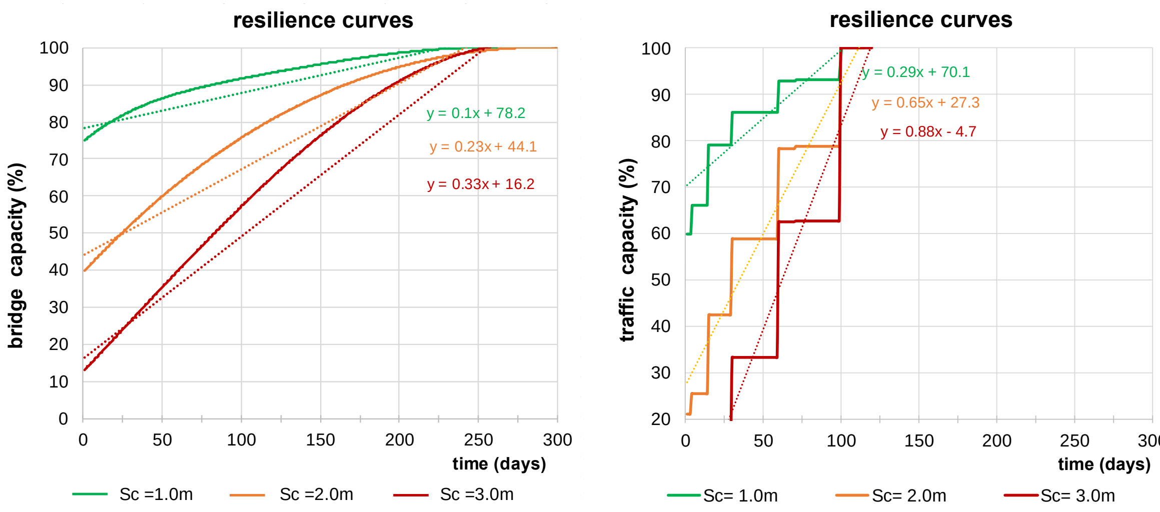
3. Evaluation of resilience curves and metrics for infrastructure assets

The representation of resilience in a graph is possible by using the fragility and restoration curves of the asset. The fragility functions assess the level of damage (measure of robustness) and the restoration functions provide a measure of the rapidity to restore the structural capacity or functionality of the asset. Following the procedure described in the previous section, the resilience curves shown in Figure 5 are generated for the same benchmark bridge (continuous lines). Figure 5a shows the resilience curves when the bridge capacity is considered as a measure of performance, while Figure 5b includes the corresponding curves for traffic reinstatement. Three scenarios are considered, corresponding to a low, medium and high hazard intensity, i.e. scour depths of 1.0, 2.0 and 4.0m, respectively. The resilience curves are produced using the damage probabilities derived from the fragility curves in Figure 3, for each of the three intensity levels, and the restoration and reinstatement curves, as per Figure 4. These ‘weighted’ resilience curves of Figure 5 show that the initial loss of structural and traffic capacity is increased for higher scour depth, which is a reasonable outcome. The reinstatement of the bridge functionality (full traffic capacity) is faster (Figure 5b), than the restoration of the bridge capacity (Figure 5a), which is also a reasonable result, as operators would keep the bridge open even though restoration tasks might be ongoing. Nevertheless, the closure of the bridge depends not only on the damage extent, but also on the ad-hoc decisions and guidelines of the road authority, the importance and the redundancy of the bridge. For example, if a bridge has a minor damage, and there is no alternative route available, the operator may decide to keep it open on full or reduced traffic capacity. This means that the reinstatement functions need to be adjusted to reflect specific decisions. In other cases, the decision for bridge closure during flood events, is taken by relying on flood level markers, without knowing the actual scour depth developed at foundations due to inability for underwater inspections, e.g. during night time or fast flowing river and exceptionally high tide. Thus, the bridge may have not been damaged, but it may take some time before it can be reopened to traffic, until the inspection of the structure by competent personnel is completed.

It is noted that the idle time, i.e. time before the commencement of any restoration work, is not included in this example. The consideration of this time would shift the resilience curve to the right, i.e. a horizontal branch in the curve following t_0, equal to a weighted idle time. The latter is estimated using an average idle time for each damage level multiplied with the corresponding damage probabilities. Typical values of minimum and maximum idle times for each damage state can be found in Mitoulis et al. (2021a). This shift of the resilience curve would result to additional losses, i.e. longer times of reduced traffic or bridge closure and larger area above the resilience curve.

Table 2 shows the values of representative resilience metrics for the benchmark bridge, using the definitions provided in Table 1 and the resilience curves of Figure 5, for both bridge and traffic capacity and the three hazard scenarios (scour of 1.0m, 2.0m and 4.0m). A linear regression curve is fitted to the resilience curves as an alternative approach for identifying their slope, which shows the rapidity of recovery. This is an approximation corresponding to the resilience triangle (see Figure 1), and even if not of high accuracy can facilitate comparisons of different resilience curves. It is observed that the restoration time is longer for the higher intensity scenarios (e.g. 300 days for S_c=4.0m), however, the restoration is more rapid in these cases (i.e. 0.29%/day for S_c=4.0m). Also, the rapidity of the traffic restoration is higher compared to the bridge restoration (e.g. 0.82 vs. 0.29 for S_c=4.0m). In this context, the resilience R is higher for lower intensity levels (i.e. 0.925 for S_c=1.0m), while R is lower when expressing bridge capacity, compared with the R that refers to the traffic capacity (e.g. 0.950 for for S_c=1.0m). Similarly, the robustness that represents the residual bridge or traffic capacity after the disruption, is higher for the less severe hazard scenario (i.e. 75.6% and 69% for S_c=1.0m).

These metrics encapsulate with a single value the robustness of the bridge and the rapidity of restoration, which makes them a descriptive measure. Hence, they can provide rapid resilience assessments for different hazard scenarios for a portfolio of assets and assist the prioritisation for interventions and allocation of resources by the infrastructure owners. Moreover, the effect of different risk mitigation strategies can be reflected directly on the values of the resilience measures. This can be achieved by updating the fragility and restoration functions and/or the idle time, when improvements are applied in the infrastructure, e.g. climate adaptation measures. These include, for example, retrofitting measures that will increase the robustness of the bridge (Freddi et al. 2021), or the use of monitoring systems, which can reduce the assessment time and lead to an earlier initiation of restoration and a more rapid recovery (Tubaldi et al. 2021, Achillopoulou et al. 2020).



(a) (b)

Figure 5. Resilience curves (continuous lines) for a bridge with shallow foundations subjected to scour depths of Sc=1.0, 2.0 and 4.0m. The performance is measured by the

bridge capacity (a) and the traffic capacity (b). The dashed lines represent the fitted linear regression curves.

Table 2. Resilience metrics for the case study bridge, based on Figure 5a for bridge and Figure 5b for traffic capacity.

	S_c= 1.0m		**S_c= 2.0m**		**S_c= 4.0m**	
	bridge	traffic	bridge	traffic	bridge	traffic
Area under the resilience curve Q(t) (t_0=0, t_h= 300 days)	277.63	285.0	245.11	269.0	218.6	255.5
Loss of resilience R' (Bruneau et al. 2003)	22.37	15.0	54.89	31.0	81.42	44.5
Resilience R (Reinhorn 2007)	277.63	285.0	245.11	269.0	218.58	255.5
Resilience R (Cimellaro et al. 2009)	0.925	0.950	0.817	0.897	0.729	0.852
Restoration time (t_1-t_0) [days]	200	100	250	115	300	120
Robustness (B-C) [%]	75.6	69	40.1	21	13.04	1.5
Rapidity ($\frac{A-B}{t_1-t_0}$) [%/days]	0.12	0.40	0.24	0.69	0.29	0.82
Rapidity (slope of a fitted linear regression to the resilience curve)	0.1	0.29	0.23	0.65	0.33	0.88

4. Resilience assessment at infrastructure system scale

Infrastructure assets comprise systems of assets in ecosystems with diverse geomorphological and topographical conditions, exposed to multiple hazards (Argyroudis et al. 2019). Available approaches for the resilience analysis of networks have been discussed in the introduction of this paper. Herein, the practicality of resilience metrics for the decision-making and prioritisation by stakeholders is illustrated, through the hypothetical road network of Figure 6, including critical transport assets such as highways (H), bridges (B), and tunnels (T). These assets are inter-dependent forming systems in series (e.g. H4-B1-B2-B3 or H2-B6-T2-T3) along a highway or a network composed of lines (H1 to H5) and nodes or intersections, e.g. B2, B6, B7. Furthermore, the infrastructure serves and interacts with other critical infrastructure and areas, such as cities, airports or industries (inter-dependencies). The infrastructure is exposed to multiple hazards, e.g. flood and scour effects (FL+Sc) as a result of extreme precipitation (PR) or sea-level rise (SLR); landslides (LS) triggered by PR or earthquakes (EQ); ground movements (GM) due to liquefaction or poor soil conditions and moisture ingress. Certain triggering hazards, e.g. PR or SLR are exacerbated due to climate change (CC), causing for example more frequent and intense FL, Sc or LS events.

The resilience for each asset can be evaluated following the steps described in section 2 and 3, adopting one or more resilience metrics of Table 1. To achieve this, appropriate fragility and restoration models are needed for each asset (H, B, T) subjected to single hazards (e.g. FL, LS, GM, EQ) or combination of hazards (e.g. Sc-EQ). The stakeholders, such as infrastructure operators or road authorities, can prioritise the assets by setting desirable resilience objectives and/or thresholds for acceptable values of the resilience metrics, e.g. on the basis of "viable minimum service levels" of the assets. This will inform resilience-based decision making for risk mitigation, in support of the design, maintenance and inspection as well as adaptation planning, e.g. to climate change conditions.

Table 3 summarises the assets and critical hazards they are exposed to, the main intra- and inter-dependencies as well as the impact (damage or functionality loss and economic impact) in case of failure. Also, the table includes indicative desirable level of resilience, which depends on the criticality of the assets for serving the community and the corresponding impact in case of damage or functionality loss. For example, tunnel T1 is expected to have higher probability for none or minor damage due to its relatively low exposure to hazard stressors and the high robustness of this type of structures. However, this is a key asset, as it provides access to an airport, especially if no alternatives routes are available (low redundancy). Hence, the demand for resilience is very high, meaning that the decision-maker would set higher thresholds of resilience in its assessment as no closure time can be tolerated in this case. Bridge B3 is possible to have higher probability for severe damage due to its exposure to multiple hazard stressors and possible deterioration, however, the impact in the functionality of the network is potentially lower, and therefore the demand for resilience is not as high as the one of other assets, e.g. B5 or B7, which are critical for businesses in the area. Yet, the decision-makers can set 'viable minimum service levels', for example the amount of time per year that B5 or B7 is acceptable to be partially non-operational due to climate conditions. This acceptance level is related to the impact on travel time and detour length (e.g. see Smith et al. 2021) or the disruption that is acceptable (e.g. in case of T1 or T2 no disruption is acceptable).

Also, the inter-dependencies of the assets are important and should be considered in the decision making. For example, the combined resilience of assets B6, T2, and T3 in series along highway H2, or B1, B2 and B3 along H4, should be considered, instead of the resilience of the individual assets. In the other hand, the impact of infrastructure failures to the society (access to residential zones), the economy (business interruption) and the environment (increased CO2 emissions, or increased noise in nature and wildlife reserve areas) are factors that are critical in the resilience-based decision-making (Lounis and McAllister 2016, Yang and Frangopol 2018).

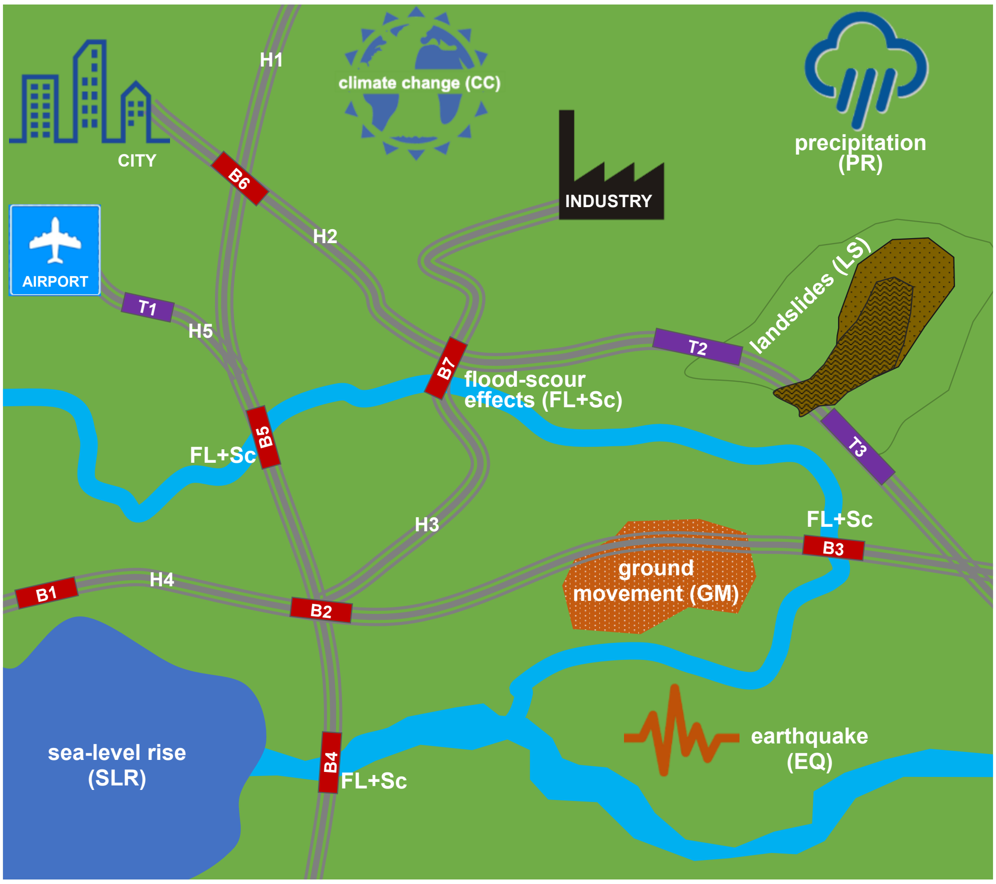


Figure 6. A simplification of interconnected transport assets including Highways (H1-H4), Bridges (B1-B7) and Tunnels (T1-T3), exposed to diverse hazards.

Table 3. Impact and resilience demand considering inter- and inrta-dependencies of transport assets exposed to multiple hazards

asset	critical hazard	inter-dependencies	intra-dependencies	impact*	resilience demand
H1	FL, PR	airport	H2, H5, H4	D, F	high
H2	FL, LS, PR	city, industry	H1, H3	D, F	high
H3	FL, EQ	industry	H1, H2, H4	d, F	high
H4	GM, FL, SLR, EQ		H1, H3	D, f	moderate
H5	FL	airport	H1	d, F	high
B1	SLR		H4	d, f	low
B2	GM		H1, H3, H4	d, F	high
B3	FL+Sc, EQ, GM		H4	d, f	low
B4	FL-Sc, SLR		H1	D, f	moderate
B5	FL+Sc	airport	H1, H5	D, F	high
B6	PR	city	H2, H1	F	moderate
B7	FL+Sc	industry	H3, H2	D, F	high
T1	FL	airport	H2	d, F	high
T2	PR		H2	d	moderate
T3	LS, PR		H2	d	moderate

** D=extensive damage, d=minor damage, F= extensive functionality loss and economic impact, f=minor/local functionality loss (as per Mitoulis et al. 2021b)*

5. Conclusions

Understanding and enhancing the resilience of critical infrastructure, such as bridges and other transport assets, requires the use of sufficient and representative resilience metrics. In this paper, available resilience metrics were summarised and discussed, aiming to provide a comprehensive, yet practical, understanding of resilience-based decision making. The most used metrics are related to the concept of the resilience curve, which describes the robustness of an infrastructure and the rapidity of recovery following a disturbance. The main steps for the generation of resilience curves and the evaluation of resilience metrics were described, and illustrative examples were provided for a benchmark bridge subject to scour effects. The use of fragility and restoration functions for the quantification of resilience through different metrics was also demonstrated. The concept of resilience-based decision making was also discussed using an illustrative example of a hypothetical road network, aiming to highlight the main factors that the decision maker should take into account, such as intra- and inter-dependencies of the assets, environmental implications or importance and redundancies of the assets.

Resilience metrics are able to quantify the effect of potential interventions and retrofitting measures as well as of improved restoration strategies. In particular, the fragility and/or restoration functions of the enhanced assets will be different compared to those corresponding to the initial design, and hence, the benefits of intervention measures can be reflected in the resilience metrics. In this way, the metrics can be employed to incorporate climate change adaptation and resilience into operational procedures as well as into the achievement of wider sustainable development benefits. For example, the use of metrics that integrate direct and indirect losses and environmental impacts in case of asset closures, can facilitate decision-making for more sustainable solutions.

Resilience metrics should be simple and practical, in an effort to be readily applicable and provide meaningful results to diverse stakeholders, who design, assess and take decisions for various critical infrastructure and hazards. Such metrics will enable an efficient cooperation between engineers, infrastructure owners and operators, the insurance industry and road authorities and a common ground to communicate prioritisation of interventions in view of the pressing climate threat. Also, resilience metrics should be accurate and informative. Hence, it is important to employ reliable methods for the quantification of the assets' robustness and rapidity of recovery, such as realistic fragility and restoration functions. Moreover, the operational procedures of the road authorities should adopt a holistic resilience-based approach, considering not only financial costs, but also sustainability effects such as ecological impact and carbon reduction.

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